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A Knowledge-Based System for Multiple Hypothesis Sensemaking Support

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Abstract - This paper takes stock on long-term research activities targeting the development of support systems for the intelligence analysts and the decision makers involved in situation analysis and sensemaking. It first reviews two notional models of situation analysis and sensemaking, which provides insights into these multifaceted processes. It then discusses the natural fit of knowledge-based systems technologies with intelligence analysis, and describes some previous work in knowledge representation, automated reasoning, and multiple hypothesis situation analysis. The current research efforts towards the integration of automated reasoning components within the multiple hypothesis framework are described. Finally, work in progress for the development of a multiple hypothesis sensemaking support system on a service-oriented architecture platform is presented.

Keywords: Sensemaking, situation modeling, knowledge representation, automated reasoning, multiple hypotheses.

1 Introduction

During the last decade or so, research activities have been conducted at Defence R&D Canada – Valcartier (DRDC Valcartier) towards the development of support systems for the intelligence analysts and the decision makers involved in situation analysis and sensemaking. These activities cover a broad spectrum going from modeling the situation analysis process to generate insights about all facets of this complex task, to the specification of a knowledge-based framework appropriate for sensemaking, through to the development of a service-oriented platform dedicated to the implementation of the most promising concepts in these areas. This paper reviews the main concepts of situation analysis and sensemaking, discusses key elements that have been previously investigated, and describes current R&D work targeting the development of a multiple hypothesis sensemaking support system (MHS3).

The paper is organized as follows. Section 2 provides definitions of situation analysis and sensemaking and briefly describes two notional models that can be used to better understand intelligence analysis. Then, as knowledge management and exploitation are key aspects of situation analysis and sensemaking, Section 3 quickly reviews some relevant work by the authors in knowledge representation and automated reasoning. Previous work in multiple hypothesis situation analysis is also summarized in Section 4, and the current research efforts regarding the integration of the automated reasoning components with the multiple hypothesis framework are described. Finally, Section 5 discusses the implementation of the MHS3 on a service-oriented architecture platform, and Section 6 provides some concluding remarks.

2 Situation analysis and sensemaking

Situation analysis (SA) is defined as a process, the examination of a situation, its elements, and their relations, to provide and maintain a product, i.e., a state of situation awareness (SAW) [1-2]. The SA process encapsulates that part of the intelligence cycle (or the decision-making cycle if one is more involved with this aspect) that is concerned with understanding the world. There is a real situation in the environment, and the SA process will create and maintain a representation of it, the situation model. In turn, a *situation* is defined as a specific combination of circumstances, i.e., conditions, facts, or states of affairs, at a certain moment.

At the highest level, making a strong parallel with the work of Endsley regarding situation awareness [3], the SA process can be decomposed into four subprocesses: situation perception, comprehension, projection and monitoring (note that we are talking processes here, not states) [1-2]. Situation perception has to do with the "acquisition" of the situation through data/information collection with various sensors and other sources. Situation comprehension is about further developing one's knowledge of the situation with respect to both its nature, i.e., the inherent character or basic constitution of the situation, and its significance or meaning, i.e., the importance, the consequence, the impact and/or the implication of the situation. This subprocess must be able to grasp the nature of the situation, and to derive operationally relevant meaning and significance from the results of situation perception. Situation projection must produce an estimate of future possibilities for situation elements, based on current trends. Finally, situation monitoring has to do with watching, observing, or checking the evolution of the situation in order to

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14. ABSTRACT
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ultimately keep track of, regulate or control the operation of the SA process.

Figure 1 presents a notional model of the SA process [1-2]. From a data-driven perspective, SA entails integrating and interpreting the whole spectrum of source data and information, ranging from radar returns to political factors. The SA process thus encompasses a vast range of activities, from the detailed signal processing associated with object/entity acquisition and tracking, to intelligence interpretation. Simply put, the process must provide answers to a great number of questions: What? Who? How many? How big? Where? What structure? When? What is it doing? Why? Build up? What could it do? How soon? What is outstanding? What has changed? Delta from expectations? What is going wrong? and many others.

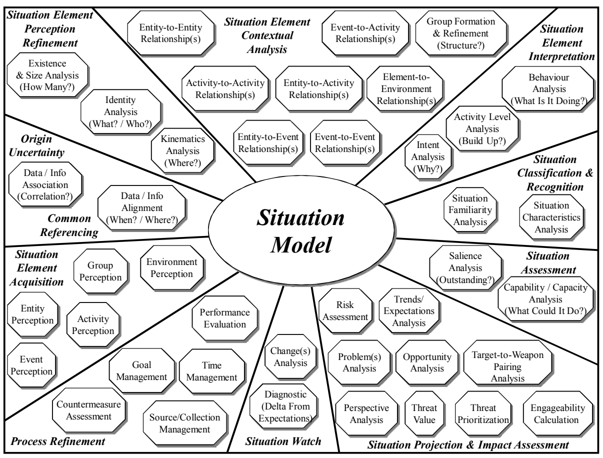

Figure 1: Notional model of situation analysis [1-2]

As suggested with Fig. 1, the SA process consists of numerous dependent and independent subprocesses, or capabilities, at multiple levels of abstraction. Every subprocess can itself be further decomposed hierarchically into multiple subprocesses. These SA capabilities must be integrated and interleaved into an overall processing flow. From a data-driven perspective, Fig. 1 suggests a sequential process (with a clockwise-rotation "feel") starting with acquisition/collection, and then going sequentially through structured description (integration/ abstraction), classification/recognition, assessment, projection, impact, and monitoring. But it doesn't have to be like that. Actually, one should note that there are no arrows on the diagram of Fig. 1. In a sense, the SA process has no *beginning* and no *end* per se. The SA process may start anywhere; there are multiple asynchronous entry points. Moreover, it is not necessarily a cycle. Actually, human information processing in operating complex systems is seen as alternating between data-driven (bottom-up) and goal-driven (top-down) processing. This alternation is viewed as critical in the formation of SAW. In goal-driven processing, attention is directed across the environment in accordance with active goals [4]. The decision maker actively seeks information needed for goal attainment and the goals simultaneously act as a filter in interpreting the information that is perceived. In data-driven (or stimulus-driven, reactive) processing, perceived environmental cues are processed to form SAW and may indicate new goals that need to be active. Dynamic switching between these two processing modes is one of the most important mechanisms underlying SAW.

Making a parallel with the service-oriented architecture (SOA) software engineering paradigm (cf. subsection 5.1), the SA capabilities (or subprocesses) of Fig. 1 could be regarded as "services" having some fair degree of autonomy. In that sense, there is a requirement that the SA capabilities must, at a minimum, communicate with one another or, ideally, cooperate with one another. The capabilities at the higher levels of abstraction must build on the results produced by the lower levels, and they also feed conclusions back to these lower levels in order to fill in unknowns.

A detailed description of the SA model shown in Fig. 1 can be found in [1-2]. Given its crucial importance within the SA process, threat analysis has been further investigated and discussed [5-7].

2.1 Sensemaking

Sensemaking is the ability or attempt to make sense of an ambiguous situation [8]. More exactly, sensemaking is the process of creating situational awareness and understanding in situations of high complexity or uncertainty in order to make decisions. Based on results from a cognitive task analysis and verbal (think aloud) protocols, Pirolli and Card [9] provide a description of intelligence analysis as an example of sensemaking. Figure 2 represents their notional understanding of the analyst's process. This is a broad brush characterization of the whole process they have seen across several all-source analysts as a way of approximating the process and orienting their studies.

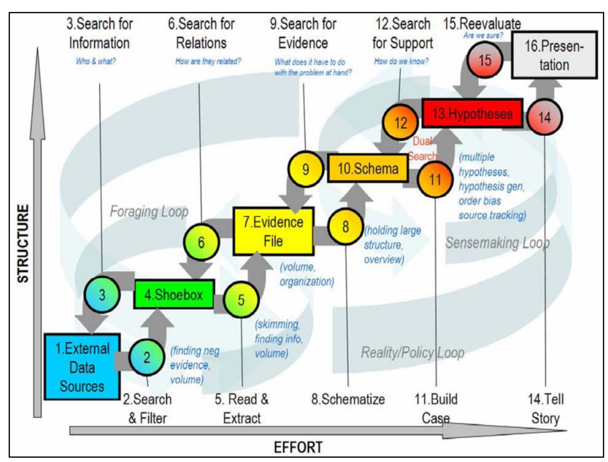

Figure 2: Notional model of intelligence analysis [9]

In the model of Fig. 2, the rectangular boxes represent an approximate data flow. The circles represent the process flow. The processes and data are arranged by degree of effort and degree of information structure. This is a process with lots of back loops and it seems to have one set of activities that cycle around finding information and another that cycles around making sense of the information, with plenty of interaction between these. This process diagram summarizes how it is that an analyst comes up with novel information.

The data flow shows the transformation of information as it flows from raw information to reportable results [9]. External data sources are the raw evidence, largely text by the time it reaches the all sources analyst. The "shoebox" is the much smaller subset of that external data that is relevant for processing. The evidence file refers to snippets extracted from items in the shoebox. Schemas are the re-representation or organized marshalling of the information so that it can be used more easily to draw conclusions. Hypotheses are the tentative representation of those conclusions with supporting arguments. Ultimately there is a presentation or other work product. Basically the data flow represents the transducing of information from its raw state into a form on which expertise can be applied, and then out to another form better suited for communication.

As previously mentioned, the overall process is organized into two major loops of activities [9]: (1) a foraging loop that involves processes aimed at seeking information, searching and filtering it, and reading and extracting information, possibly into some schema, and (2) a sensemaking loop that involves iterative development of a mental model (a conceptualization) from the schema that best fits the evidence. Information processing in Fig. 2 can be driven by bottom-up processes (from data to theory) or top-down (from theory to data). The analysis of Pirolli and Card suggested that top-down and bottom-up processes are invoked in an opportunistic mix.

2.2 Models overlap and complementarity

Clearly, the notional models of Figs. 1 and 2 overlap on many aspects. But there is also a fertile complementarity between them. While the situation analysis model of Fig. 1 focuses more on the components of a situation, the model of Pirolli and Card gives emphasis to the cognitive processes of an intelligence analyst that is trying to acquire and develop knowledge about such components. Both models could thus be used together to structure the intelligence analysis process and provide an adequate foundation for the development of situation analysis and sensemaking support systems.

Actually, these models can be used to better understand the intelligence analyst problem space, i.e., to map the problems (e.g., user requirements, horizon scanning, etc.) on the models, and also regarding the technology space, i.e., to map the technology (e.g., COTS, GOTS, industry, academia, varying technology readiness levels) on the models. This way, problems are mapped to potential tools, and tools are mapped to the capability they offer. This enables the generic application of tools to various areas in the problem space and helps to distil out where technology already exists to address particular problems. It highlights where there are problems but nothing in the technology space addressing it (leading to further development), and the potential technologies that could be of benefit when advanced in technology readiness level (TRL). The tools/technology space can then be readily mapped to some service-oriented framework (cf. subsection 5.1) so that a structure for the service delivery can be articulated.

3 Knowledge-based framework

The idea of awareness ultimately has to do with having knowledge of something. In addition to the cognition facet, awareness is also linked with the notions of perception and understanding/comprehension. While perception is defined as the result of becoming aware of something through the senses, comprehension and understanding are both defined as the knowledge gained by grasping, with the intellect, the nature, significance, or meaning of something.

Such considerations have led us to develop and adopt a knowledge-centric view of situation analysis and sensemaking. Within our research activities, aspects of knowledge, and how it can be acquired from experts, formally represented and stored in knowledge bases to be exploited by computer programs, and validated have been initially discussed in [10]. The benefits and issues related to the use of knowledge-based systems technologies in the context of situation analysis support systems (SASSs) were then discussed at length in [11-12]. The key related aspects of knowledge representation concepts, paradigms and techniques, and reasoning processes, methods and systems, and knowledge and ontological engineering techniques for use in developing knowledge-based SASSs were further investigated and discussed in [13-15].

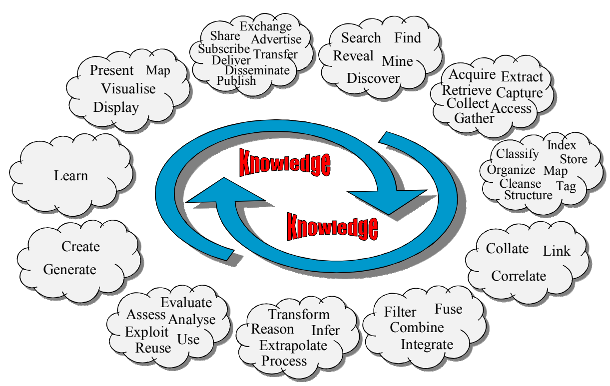

Figure 3: Knowledge management and exploitation

Instead of providing a crisp definition of knowledge management and exploitation (a difficult task that often leads to controversy), Fig. 3 illustrates what it is that one typically does with knowledge. As for the models of Figs. 1 and 2, Fig. 3 can be used to provide an adequate foundation for the development of situation analysis and sensemaking support systems, and to guide the development of specific knowledge management and exploitation (KME) tools, which can eventually be mapped to some service-oriented framework (cf. subsection 5.1).

3.1 Knowledge representation

The object of knowledge representation (KR) is to express knowledge in computer-tractable form, such that it can be exploited [13]. Figure 4 illustrates different categories of knowledge that are relevant to support the situation analysis activities of an analyst in the intelligence domain.

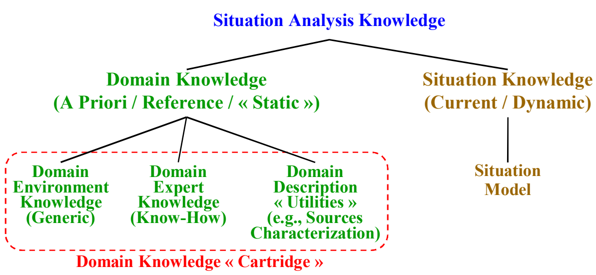

Figure 4: Categories of situation analysis knowledge

To enable the representation of such knowledge, the knowledge-based framework developed at DRDC Valcartier allows for the use and manipulation of a number of knowledge representation building blocks [16]: ontologies, facts, inference rules, text-based templates, etc. Among these, the notion of a « fact » (and that of an « atom definition ») has been adopted as a key knowledge representation paradigm [16]. In our framework, as shown in Fig. 5, a fact is defined by a name (i.e., a label) and a list of arguments with a precise type and order.

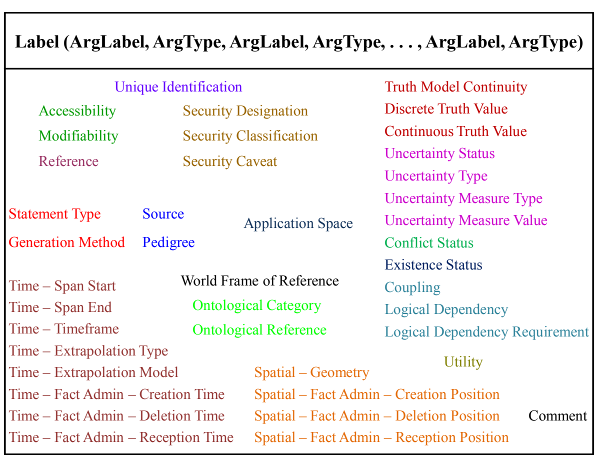

Figure 5: Example of fact attributes

An example of a fact could be « Is Exposed To (Mike, Radiation, Uranium) » to formally express the idea that "Mike is exposed to radiations caused by uranium". A number of attributes (Fig. 5) are also attached to the fact as metadata to provide a wide variety of contextual information regarding uncertainty, temporal and spatial issues, security, the source of the fact, etc.

Among the contextual attributes attached to a fact are those related to the temporal domain (some of which are illustrated on Fig. 6). Such attributes are used to support the management of the fact over time, and temporal reasoning.

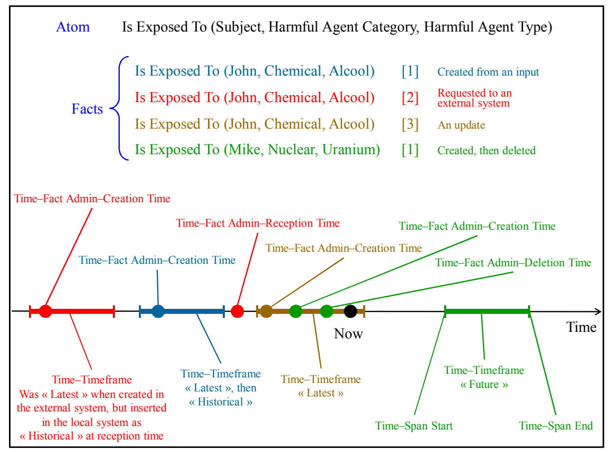

Figure 6: Fact attributes to establish the temporal context

Figure 7 illustrates similar contextual attributes that are used to support the spatial management of a fact, and spatial reasoning.

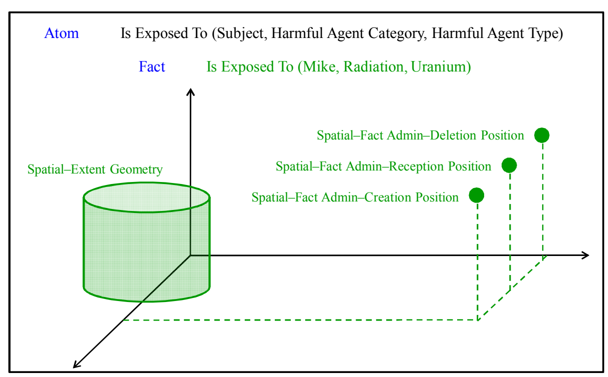

Figure 7: Fact attributes to establish the spatial context

3.2 Automated reasoning

Not all of the situation elements of interest are directly observable with sensors. This is especially true of highly abstract types of situation elements (e.g., enemy intent), and also of the relationships between the situation elements. Those aspects of interest that cannot be directly observed must be inferred, i.e., derived as a conclusion from facts or premises, or by reasoning from evidence. In this regard, Fig. 8 shows the environment that has been created to enable the inference of situational facts through automated reasoning (ISFAR) through the synergistic exploitation of the complementary strengths and expressiveness characteristics of different knowledge representation approaches, and corresponding reasoning paradigms [17].

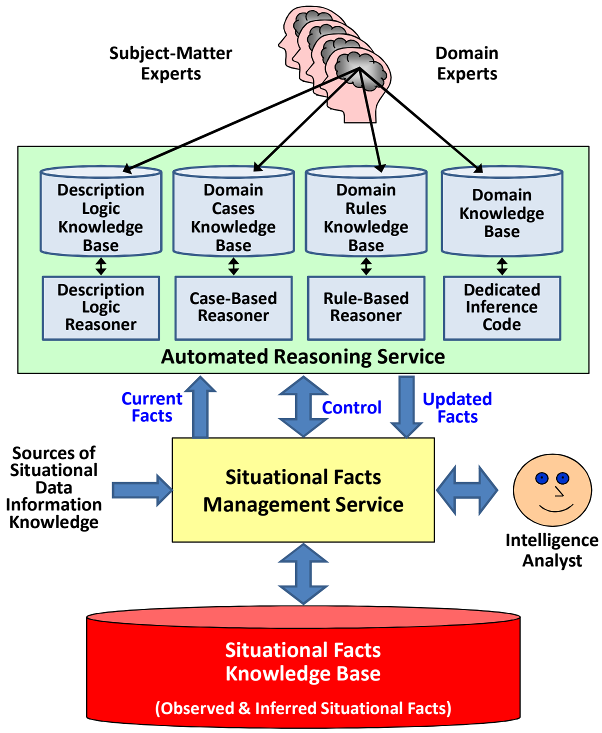

Figure 8: Inference of situational facts through automated reasoning (ISFAR) [17]

In our framework, the ISFAR concept has been implemented as a set of independent services (cf. subsection 5.1) performing rule-based [18], description logic [19] and case-based [20] reasoning. A module for kinematics and geospatial analysis has also been implemented as specific, dedicated inference code [17].

4 Multiple hypothesis sensemaking

Uncertainty makes the analysis of even simple situations difficult. It forces intelligence analysts to formulate and manage hypotheses during the construction of explicit representations of real world situations (Note that the generation and management of hypotheses is an explicit component of the sensemaking model proposed by Pirolli and Card [9]). This may quickly become overwhelming. To provide better support to the intelligence staff, the main concepts behind multiple hypothesis tracking have been revisited to develop a proof-of-concept prototype of a multiple hypothesis situation analysis (MHSA) support system [21-23].

For the MHSA prototype, a graphical language has been defined and made available to the analyst for the construction of explicit representations (or models) of the situations under examination. This language, shown in Fig. 9, allows the intelligence analysts to define and manipulate *situation model components* (SMCs) to create graphical representations of situations. The language is limited to five types of SMCs that can be used by the analysts: 1) *Element*, 2) *Undirected Relation*, 3) *Directed Relation*, 4) *Relation Origin Connecting Point*, and 5) *Relation Destination Connecting Point*. Everything that an analyst has to say about a given situation must be expressed using only these five types of SMCs.

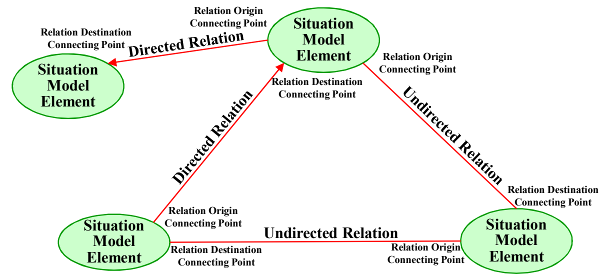

Figure 9: Graphical language for situation modeling [22]

Within the proposed MHSA framework, one says that there is uncertainty when there are more than one possibility for a given situation model component [21-23]. Moreover, when there are multiple possibilities for a situation model component, these possibilities *must be mutually exclusive*; if one is true, then all the others are necessarily false. When there is only one possibility for a situation model component, then this possibility is considered as « certain ».

Figure 10 shows a conceptual view of the proof-of-concept prototype of a multiple hypothesis situation analysis support system (MHSA-SS) that has been developed at DRDC Valcartier. Details can be found in [21-23].

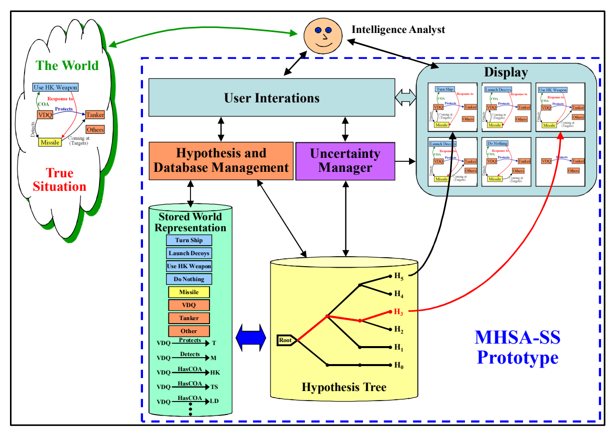

Figure 10: Conceptual view of the MHSA-SS prototype

Current research efforts at DRDC Valcartier investigate the integration of the automated reasoning components (i.e., the ISFAR framework) with the multiple hypothesis framework (i.e., the MHSA-SS prototype) to develop a multiple hypothesis sensemaking support system (MHS3). Figure 11 shows the high-level interactions of the main components required to achieve MHS3.

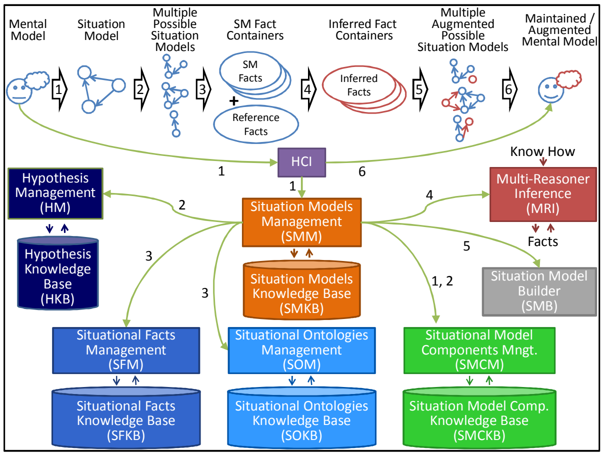

Figure 11: Components high-level interactions for MHS3

The MHS3 provides tools to support the construction of a situation model representing the analyst's mental model of the situation (1). Actually, through the MHSA framework, the analyst can construct and maintain multiple possible situation models in parallel (2). If the formalism of facts and ontologies (cf. subsection 3.1) is used for the construction of the situation models (3), then the automated reasoning components (4) can be applied to distinct sets of facts corresponding to distinct situation models (i.e., distinct hypotheses). The resulting sets of inferred facts obtained from the different reasoners can then be used to generate multiple augmented possible situation models (5) supporting the maintenance or augmentation of the mental model of the analyst (6).

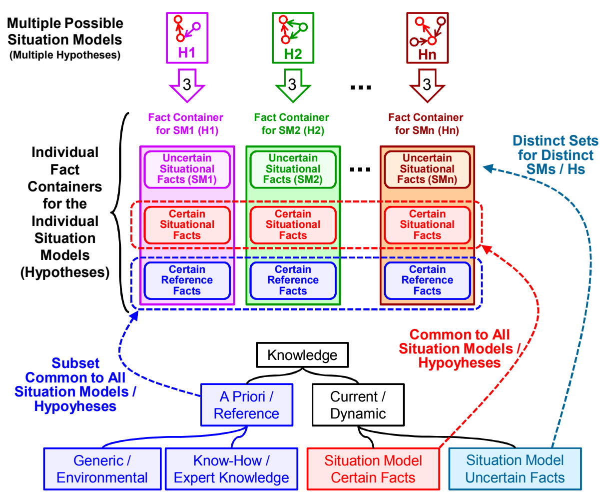

Figure 12: Fact containers for the situation models

Figure 12 illustrates how the distinct fact containers corresponding to the distinct situation models (or, equivalently, the distinct hypotheses) are created from the different knowledge categories. These fact containers are required for step (4) of Fig. 11. Note that the notions of « certain » versus « uncertain » facts on Fig. 12 refer to the MHSA framework where « certain » components are contained in all hypotheses and « uncertain » components are specific to particular hypotheses.

Each individual fact container of Fig. 12 is sent to the automated reasoning component, i.e., the multi-reasoner inference (MRI) component of Fig 11, at step (4) of Fig. 11. Depending on the particular facts involved and on the « know-how » provided to this reasoning component, new facts will potentially be generated (the inferred facts on Fig. 11). Then, at step (5), the initial set of situational facts, the new inferred facts, and a subset of the reference facts (the ones that have been involved in the generation of the inferred facts) will be used by the situation model builder (SMB) component of Fig. 11 to create an augmented situation model corresponding to all these facts. This is illustrated in Fig. 13.

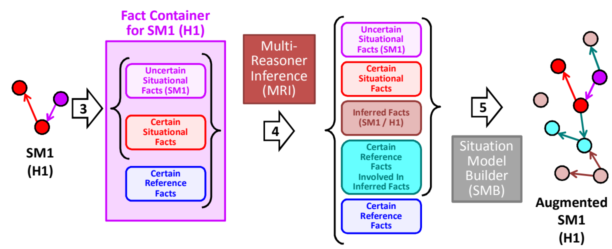

Figure 13: Generation of an augmented situation model

Facts are typically statements made about the instances of an ontology. If all of the facts used in the MHS3 framework are forced (by the system) to only represent 1) a situation element (i.e., an atomic unary fact with only one ontology instance in its argument list, e.g., « Exist (Mokami) ») or 2) a binary relation (i.e., an atomic fact with only two instances in its argument list, e.g., « Owner (Mokami, John Doe) »), then the construction of a situation model from a set of facts can be fully automated. Otherwise, if the system manipulates arbitrary formal facts without restrictions, then the situation model builder component will require human intervention to deal with the potentially complex semantics of such facts.

5 MHS3 implementation platform

Many of the concepts discussed above for MHS3 have been initially implemented as a set of tools within the Multi-Intelligence Tools Suite (MITS) developed by the Intelligence and Information (I&I) Section at Defence R&D Canada – Valcartier (DRDC Valcartier) [16]. The MITS is a federation of innovative, composable and interoperable intelligence related tools, which are integrated and interleaved into an overall, continuous process flow relevant to the intelligence community.

As a result of the experience gained through the incremental development of the MITS so far, a number of lessons learned have been formulated regarding design and implementation approaches and enabling technologies. Among these, the need for a more suitable integration platform and the evolution towards a different human-computer interaction layer are briefly discussed next.

5.1 Intelligence S&T Integration Platform

The efficient development of a suite of integrated tools like the MITS also brings forward some integration requirements and issues at the software system level. In response to these, the I&I Section at DRDC Valcartier has proposed and developed the Intelligence S&T Integration Platform (ISTIP). Using open source Web services technologies and service-oriented architecture (SOA) design principles, the ISTIP provides a backbone, integration reference platform for the iterative and incremental development and integration of the innovative, loosely coupled, reusable, composable and interoperable services required to perform tasks in computer-based intelligence support systems.

The SOA paradigm has been put forward for the ISTIP with the goal to achieve a number of (long-term) benefits: improved integration (and intrinsic interoperability), inherent reuse, increased leveraging (including leveraging of the legacy investment), streamlined architectures and solutions (through the concept of composition), establishing standardized data representation, focused investment on communications infrastructure, "best-of-breed" alternatives, and organizational agility.

The services developed for the ISTIP must meet a number of SOA design principles:

- Loose Coupling – Services maintain a relationship that minimizes dependencies and only requires that they retain an awareness of each other.
- Service contract – Services adhere to a communications agreement, as defined collectively by one or more service descriptions and related documents.
- Autonomy – Services have control over the logic they encapsulate.
- Abstraction – Beyond what is described in the service contract, services hide logic from the outside world.
- Reusability – Logic is divided into services with the intention of promoting reuse.
- Composability – Collections of services can be coordinated and assembled to form composite services.
- Statelessness – Services minimize retaining information specific to an activity.
- Discoverability – Services are designed to be outwardly descriptive so that they can be found and accessed via available discovery mechanisms.

At this moment, a number of services aligned with the principles described above have already been implemented and are available on the ISTIP. Many more services will continuously be created as legacy tools and systems are converted, and as the research activities of the I&I Section at Valcartier further progress. Ultimately, there will be a close match between the services on the ISTIP and the notional models discussed in Section 2.

5.2 Interaction Interface Layer

Clearly, providing all of the services of the ISTIP is not sufficient to achieve the concept of the MHS3. One also needs some human-computer interaction front-end for the exploitation of these services. This front-end is called *VOiiLA* (Visionary Overarching Interaction Interface Layer for the Analysis). All services of the ISTIP combined with VOiiLA constitute the MHS3 implantation platform.

5.3 Implementing MHS3 on the ISTIP

Work is in progress to implement the MHS3 framework as a set of services on the ISTIP (Fig. 14). Many of these services already exist on the ISTIP at this moment. Examples are the services for the semantic annotation of unstructured text documents (SATD), the automated facts extraction from unstructured text documents (AFEXTD), the situational spatial features management (SSPFTM), the situational facts and ontologies managers (SFM and SOM), and the reasoners of the automated reasoning suite. Other services are currently being developed to support the multiple hypothesis framework.

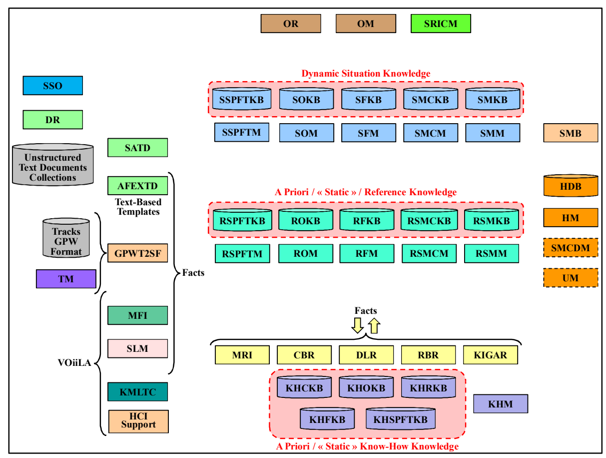

Figure 14: Work in progress for the MHS3 on the ISTIP

6 Conclusion

This paper provided definitions of situation analysis and sensemaking and briefly described two notional models that can be used to better understand intelligence analysis. Then, as knowledge management and exploitation are key aspects of situation analysis and sensemaking, some relevant work by the authors in knowledge representation and automated reasoning were briefly reviewed. Previous work in multiple hypothesis situation analysis was also quickly summarized, and the current research efforts towards the integration of the automated reasoning components with the multiple hypothesis framework were described. Finally, work in progress for the implementation of the MHS3 on a service-oriented architecture platform was presented.

Although our research work is progressing pretty well at the moment, the automation of the main components of the proposed MHS3 framework remains a serious research challenge at this stage. This is especially true regarding the automated generation of hypotheses from observation data, and automated generation of situation models from sets of situational facts.

Finally, it is worth mentioning that others are also proposing similar knowledge-based approaches to intelligence analysis and sensemaking, including the development of service-oriented solutions. In this regard, the work of Bray [24-25] is of particular interest.

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